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RESEARCH MEMORANDUM

SMOKE STUDIES OF SECONDARY FLOWS IN BENDS, TANDEM CASCADES, AND HIGH-TURNING CONFIGURATIONS

By Arthur G. Hansen, Howard Z. Herzig, and George R. Costello

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Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
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2797

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SUMMARY

Flow-visualization studies, using smoke, were made of the secondary flows in rectangular bends, tandem cascades, and high-turning configurations. The roll-up of the wall boundary layer of a rectangular bend forms a passage vortex near the suction surface similar to that previously observed for cascades. The vortex so formed then shifts out into the main stream. Because of leading-edge effects, the boundary-layer flows in bends were found to be sufficiently different from the flows in blade rows to make direct application of bend results to blade rows inadvisable.

Passage vortices are shown, in the tandem-cascade study, to resist turning with the main stream through which they pass and to disturb the flow in subsequent blade rows. This disturbance may explain in part the appreciable size of the losses sometimes attributed to secondary flows in turbomachines despite the fact that the energy involvement in vortex formation is slight.

Tip-flow studies of high-turning blades with relative motion between blades and end wall indicated that if the relative sizes of the passage vortex forces, the tip clearance forces, and the blade-scraping effects are properly controlled, it may be possible to improve the blade-tip loading characteristics in turbomachines.

INTRODUCTION

Photographs of the patterns of secondary flow in blade rows have been obtained by recent investigations using flow-visualization techniques (refs. 1 to 4). Careful application of these visualization techniques made it possible to present direct evidence of the flow paths in boundary layers. It was considered desirable to use experimental techniques (flow visualization) in order to avoid fundamental simplifying assumptions which necessarily qualify the results of a theoretical analysis.

The roll-up of the wall boundary layer at the inlet of a two-dimensional cascade and the formation of the so-called passage vortex is described in reference 1. The roll-up into a vortex is shown to occur well up in the passage and not to be a trailing-edge phenomenon. These same results are found over a wide range of Mach numbers and for an annular cascade as well. The flow-visualization techniques employed are presented in reference 1 together with tests to demonstrate the validity of the results obtained by the various methods involved.

2797

A general conclusion is reached in reference 1 regarding the inapplicability of two-dimensional and quasi-three-dimensional analyses to the boundary-layer flows even under the most favorable conditions. It is further noted that the large pressure and angle gradients involved in the vortex region especially, and in the entire boundary layer as well, severely limit the accuracy of measurements taken there.

For these reasons, it was considered inadvisable to attempt to extend the investigation begun in reference 1 to more general configurations using analytical techniques. Accordingly, in reference 2, the influence of blade geometry on secondary flows was investigated qualitatively by independently varying stagger angle, aspect ratio, solidity, and angle of attack and using blade fillets in the two-dimensional cascade. As a result of these experimental investigations, reference 2 concludes that the size and "tightness" of the passage vortex is influenced only by those parameters which involve the turning of the main flow. Furthermore, the presence of fillets on the blades did not prevent the passage vortex roll-up.

The effects of tip clearance and some of the effects of relative motion between blades and end-wall wire are also studied in reference 2. Tip clearance, far from alleviating secondary-flow losses, provided an additional flow disturbance in the form of a "tip clearance vortex" side by side with the passage vortex and rotating in the opposite direction. With relative motion between blades and wall for the configurations in reference 2, the blades were seen to exert a scraping effect on the fluid entrained near the wall, resulting in a roll-up of boundary-layer fluid at the leading surfaces of the blades. Some effects of this roll-up on tip loading characteristics were investigated briefly. The results indicated improved tip loading characteristics with the blade pressure surfaces leading (with respect to the relative blade-to-wall motion) and worsened tip loading characteristics with the blade suction surfaces leading, for configurations similar to those in reference 2.

References 3 and 4 extend the results of reference 1 to annular cascades. In these references, some striking visual evidences of large inward radial flows along paths in the blade wakes and in some regions of thickened blade boundary layer on the blade suction surfaces are presented. At one flow condition in reference 4, these inward radial flows accounted for 65 percent of the low-energy fluid found near the inner shroud downstream of the blades.

While references 1 to 4 provide qualitative information about certain fundamental aspects of secondary flows, they cover only a portion of the field of research currently devoted to these flows. Several of these topics, which are of particular current interest and of possible importance in application to turbomachine design, were studied at the NACA Lewis laboratory, by means of smoke visualization and are reported herein.

2797

For example, a large portion of current secondary-flow investigations is devoted to the study of such flows in bends or elbows (ref. 5). Because of the widespread interest in this phase of the problem, the flow-visualization technique was applied to several bends and the results presented herein. A comparison between the boundary-layer flows in such bends and in cascades of blades having the same turning sections is likewise provided. Other studies of general interest presented herein concern the secondary flows in stationary tandem cascades and the effects of relative motion between end wall and blades with high turning.

APPARATUS AND TEST PROCEDURE

Cascades

The experimental setup of reference 1 was suitably modified for the conduct of the tests on flows in bends and high-turning cascades. The blade row of 65-12-10 blades was replaced by circular arc blades made of sheet aluminum and mounted in the tunnel. The moving-wall tests were conducted in the cascade with a 45° stagger angle using blades having 125° of turning.

A 0°-stagger-angle configuration was used for all the other studies in this report.

Bend and Blade-Row Construction

Two sets of rectangular bends, or elbows, with the curved surfaces made of sheet aluminum, designed for 60° and 45° turning, respectively, were used for this investigation. (All configurations discussed herein will be shown in the figures. An insert appears on each of the photographs depicting schematically an overhead view of the configuration and the smoke trace appearing in the photograph.) The turning was done by circular arc sections. Straight sections were provided for guidance at the inlet and discharge of the turning arcs resulting, in effect, in a row of rectangular elbows. The 60°-bend configuration was the same as a 60°-blade-row configuration also used herein except for the inlet guidance section. The construction of the 45°-bend configuration was somewhat different. Similar straight guidance sections were provided but the turning sections were made of concentric circular arcs in order to obtain nearly circular streamlines in the main flow field.

One end wall of the tunnel was replaced by a Lucite sheet to permit the photographing of the smoke traces at the other wall from directly overhead. This was intended to give another view of the streamline paths other than the high-angle projection shots taken at the discharge section looking upstream. When viewed in this direction, perpendicular to the plane in which they are flowing, the streamlines appear quite faint and therefore it is considerably more difficult to obtain good high contrast pictures from above than from downstream.

The blades for the tandem cascades were similarly made of sheet aluminum. Each of the two blade rows of the tandem cascade was mounted on an individual aluminum strip, thereby enabling the positions of the two blade rows to be shifted relative to each other in both the blade-to-blade and axial directions.

Test Procedures

As in reference 2, relative motion between blades and wall was accomplished by replacing one of the end walls with an endless moving belt, the speed and direction of which could be varied.

These tests were all conducted at low air speeds, 30 feet per second, and the secondary-flow patterns were obtained by means of the smoke visualization method described in reference 1.

RESULTS AND DISCUSSION

Secondary Flow in Bends

It has been noted in the literature (cf. ref. 5) that low-stagnation pressure fluid in the end-wall boundary layers of rectangular bends moves across the passage from the pressure toward the suction side. It has been further indicated that upon reaching the suction surface, the low-stagnation pressure fluid is displaced away from the wall and out into the main stream.

The smoke flow-visualization technique was applied to the study of the boundary-layer flow in two sets of rectangular bends with the following results.

<u>45° bends</u>. - As noted earlier, the curved walls of these 45° rectangular bends were concentric circular arcs in order to make the main-flow streamlines as nearly circular as possible in the turning section of the elbow.

Figure 1 shows the typical passage vortex formation pattern described for cascades in references 1 and 2. The smoke was introduced at the wall and near the pressure surface of the bend. It can be seen to cross the passage and to roll up near the suction surface. Because of the greater turning involved here than in references 1 or 2, the roll-up and vortex formation are much more distinct, thus enabling more satisfactory photographs of the passage vortex phenomenon to be obtained than previously.

2797

The smoke filament in any of these pictures actually traces out the path of only one of the streamlines which comprise a passage vortex. Because of the symmetry of the flow in such a vortex, however, the behavior of any one streamline in the vortex can be considered representative of the entire vortex flow. Accordingly, in this report when the roll-up of a streamline into a vortex is shown, it will be characterized as the entire vortex in the discussion of the figure.

Figure 2 shows another view of a part of the passage vortex taken with the camera pointed almost directly upstream into the vortex. Careful examination of this photograph discloses that the portion of the passage vortex shown does not actually touch the suction surface. The outer portion of this vortex which does contact the suction surface could have been obtained by admitting smoke away from the wall up on the pressure surface of the passage. This is in accordance with the pattern of passage vortex formation described in reference 1, that is: The boundary layer roll-up is such that the outer layers of the passage vortex are derived from inlet boundary-layer flow near or on the pressure surface side of the passage; the central portions of the passage vortex are derived from the inlet boundary layer nearer the suction side of the passage.

Another view of the passage vortex is presented in figure 3. Here, the vortex is clearly shifting in a direction away from the wall and the suction surface with axis in the direction shown in figure 3. Reference 5 notes the displacement of the accumulation of secondary-flow material but not that the accumulation is a flow vortex. Figure 4 was obtained by increasing the amount of smoke introduced at the inlet.

60° bends. - The formation of a passage vortex in the wall boundary layer of the 60° rectangular bend is shown in figure 5. The turning sections of these passages are circular arcs, all having equal radii of curvature.

An overhead view of the deflection of a boundary-layer streamline across the passage is presented in figure 6(a). Note that this streamline does not actually contact the suction-surface side of the passage, that is, this streamline is not in the outermost layer of the vortex. For figure 6(b), the smoke was admitted up on the pressure surface of the bend, about 1/4 inch away from the end wall. In this case, the streamline pictured is one which does actually reach the suction surface across the passage.

Comparison of Secondary Flow in Bends and Cascades

A comparison is made in this section of the secondary-flow patterns obtained with the rectangular bends having a turning angle of 60° and with the two-dimensional cascade of sheet-metal blades having a turning angle of 60°. The sole difference between the two setups is in the guidance sections of the bends at the inlet of the turning section. The total turning, the rate of turning, and the blade spacing are the same for both configurations. With the exception of the leading-edge region, the main-flow streamline patterns were likewise found to be the same.

2797

Figures 7(a) and 7(b) show two of the streamlines in the end-wall boundary layer of the 60° cascade which roll up in the passage vortex. Figure 7(c) shows that some of the fluid in the passage vortex for this configuration comes from up on the pressure surface of the blade at a distance from the wall.

In figure 8, the smoke is admitted at the inlet to the blade row and at the wall but closer to the pressure surface than in figures 7(a) and 7(b). It appears from figure 8 that in this 60° turning cascade of sheet-metal blades (with the tangent to the blades at the inlet being in the axial direction), there is a well-defined stagnation region near the blade leading edges on the pressure-surface side. The smoke trace in the photograph approaches this region, divides in two, and flows around it. One part of the smoke follows a cross-channel flow pattern; the other part flows around the blade leading edge and downstream along the blade suction surface in the adjoining passage. An overhead view of this phenomenon appears in figure 9.

This difference in behavior of the boundary layer of the cascade and the bends can be explained qualitatively as follows. The main streamline pattern for the given cascade should have the form depicted in figure 10(a), that is, a stagnation point should exist on the pressure surface of the blade slightly downstream of the leading edge. The adverse pressure gradients in the vicinity of the wall immediately upstream of the stagnation point which must exist in this region give rise to the separated-flow area. In the elbow configuration previously discussed, such a stagnation region on the pressure surface does not exist. The main streamline pattern should have the form shown in figure 10(b) because the straight entrance section affords a gradual loading of the turning surfaces. Thus, despite the fact that the mean streamlines through the passage are relatively the same for the 60° bend and for the corresponding cascade, the boundary-layer flows are considerably different.

In figure 11(a) the probe admitting the smoke has been shifted toward the suction side of the passage just enough for the smoke trace to clear the stagnation region. The path of the smoke trace, by comparison with figure 6(a) for the 60° bend, can be seen to be somewhat distorted. In figure 11(b) the probe has been moved even closer to the suction side, yet the flattened trajectory of the cross-channel flow path still is evidence of the effects of the separated-flow region.

2797

The study of secondary flows in a rectangular bend may then facilitate theoretical analyses of flow deflection paths, but the results may not be applicable directly to cascade boundary-layer flows.

Secondary Flow in Tandem Cascades

The two tandem cascades were made with sheet-metal blades bent in circular arcs to give a turning of 60° each. The upstream cascade turned the flow 60° from the axial direction (to the left as seen in fig. 12). The second, or downstream, cascade turned the flow back to the axial direction (to the right as pictured in fig. 12). The main stream followed this turning smoothly and evenly.

The secondary-flow pattern in the wall boundary layer for each 60° cascade was the same as shown earlier; that is, each one generated its own passage vortex which then extended downstream.

The behavior of the vortex generated by the upstream cascade provided the chief interest in this flow-visualization study. This vortex did not turn as much as the main-stream flow as it passed through the downstream cascade. Instead, it displayed a strong tendency to continue in the direction it was going when it left the upstream cascade. When the relative spacing of the cascades was such that this vortex passed through the downstream cascade without touching a blade, it was not turned back to the axial direction. Because of the setup used, it was not possible to get overhead pictures of this phenomenon so that the discharge angle of the vortex might be ascertained. The best estimate that could be made in this series of qualitative studies is that the vortex tube does turn somewhat in passing through the second blade row but that the discharge angle of the vortex is nearer 60° from axial than axial.

A striking manifestation of the resistance to turning of the vortex is provided in figure 12. In figure 12(a), the smoke was introduced at the inlet to the upstream cascade and at the wall. The smoke trace is seen to cross the passage in this cascade. The deflection of the streamline away from the wall also is apparent from its spanwise position in the photograph as it enters the second, or downstream, cascade. Then, as seen in figure 12(a), the vortex instead of turning with the main flow proceeds in its path until it collides with the pressure surface of a blade in the second cascade. An observer at the tests could see the flow in the vortex strike the pressure surface and bounce off downstream. At the low air speeds of these tests, flow separation appeared to occur on the pressure surface of the blade in the region of the impact. Figure 12(b) shows the same phenomenon when the smoke is introduced at a different position in the inlet boundary layer of the first cascade.

The preliminary results of these tests indicate one fashion in which the secondary flows, with little actual energy involvement per se, may give rise to considerable losses as a result of their behavior in subsequent stages of turbomachines. This behavior pattern of the vortex tubes suggests the need for further investigations into the nature of the vortices, how they penetrate the main flow field, and what becomes of the main flow in the vicinity of the origin of the rolled-up vortex and along its path.

2797

Tip Clearance Effects with High-Turning Blades

As noted in reference 2, the blade-tip clearance flows and the scraping effects produced by relative motion between blades and wall may lead to poor blade-tip loading characteristics in a turbine rotor. This condition would result in less work being extracted from the gas at the tip section. Total-temperature measurements behind turbine rotors generally indicate that this is actually the case.

However, in several recent experimental investigations of high-speed turbines at the Lewis laboratory, this quite typical decline in turbine-blade performance at the tip sections was notably absent. The turbine-blading configurations involved were fairly typical of high-speed turbine rotors, that is, large-turning and high-twist blades. Consideration of these results along with those of reference 2 suggested the possibility that under certain conditions a balance might be established between the passage vortices, the tip clearance vortices, and the scraping effects which would enhance good blade-tip loading characteristics.

It was reasoned that the scraping effect, which in the configuration of reference 2 was so large that it masked completely the passage and tip clearance vortex effects, would be reduced considerably when the blade-tip orientation was more tangential in direction. The chord line of the tip section of high-twist blades is pointed more nearly in the direction of the relative blade-wall motion than in reference 2. Physicially such blades might be considered to have a slicing action on the wall boundary layer rather than the kind of scraping action seen in reference 2. It was reasoned further that the tip clearance vortex would become larger with higher turning in the blades as a result of the increased gradient of pressure from the pressure to the suction surface of the blade. It had already been established that the passage vortex becomes larger with increasing turning. As has been previously noted, some of the flow forming the vortex comes off of the pressure surface of the blade. This effect might be somewhat reduced by the tip clearance action to direct into the tip clearance vortex some of the boundary-layer flow which would, with a stationary wall, otherwise deflect off of the blade pressure surface, onto the wall, and across into the passage vortex. Smoke studies were conducted in the two-dimensional cascade with the moving wall to investigate these possibilities. A cascade with a 45° stagger angle was used to permit large turning.

2797

Photographs of the results of an investigation of blades with approximately 125° turning are presented in figure 13. In this configuration, the blades have zero angle of incidence with the main flow, and the trailing edges of the blades point approximately 10° from the direction of the moving wall motion. A schematic sketch of the apparatus appears in figure 13(a).

Because of the high turning of the cascade blades, the camera had to be directed broadside at the smoke and could not be aimed along smoke paths. This necessitated the use of large quantities of smoke to obtain any photographs at all. The photographs which were obtained are of projected smoke patterns only.

In figure 13(b) the smoke was introduced with the probe at the leading edge of the middle blade of the cascade, on the pressure surface side, (the photographs show suction surfaces only) and spanwise about one third of the way up the blade. The wall is stationary. Some of the smoke deflected down the pressure surface and through the tip clearance space forming a very large tip clearance flow region on the suction side of this blade. This tip clearance flow can be seen against the suction surface of the middle blade in figure 13(b). The excess of smoke which did not follow this pattern can be seen passing downstream to the right in the photograph. No suitable photographs were obtained of the passage vortex roll-up. This was observed to occur in the upstream third of the passage and to roll around the large region occupied by the tip clearance flow, making a sharp surface of demarcation defining this region.

With the wall moving at moderate speed (fig. 13(c)), the tip clearance flow, seen against the suction surface, was observed to have been reduced considerably in magnitude. The region occupied by this flow was correspondingly reduced with the result that smoke introduced in the boundary layer at the passage inlet could now more closely approach the suction surface than when the wall was stationary.

With the wall moving at a higher speed (fig. 13(d)), no tip clearance flow to the suction surface was observed. Smoke introduced in the inlet boundary layer for the most part flowed quite smoothly downstream. This indicates that a balance was established between the passage vortex forces and scraping effects on the one hand, and those powerful forces that tend to create clearance flow on the other hand; this balance resulted in relatively undisturbed flow throughout the passage. As a matter of fact, the flow through the passage under these conditions was smoother than in many earlier configurations, where lower turning and smaller tip clearance forces were involved.

2797

It may be inferred, therefore, that the possibility certainly exists of designing high-speed turbine-rotor configurations in such a fashion as to prevent reduced loading on the blades at the tip section. This possibility depends upon evaluating and regulating the relative sizes of the secondary and blade-end clearance flow effects. This also suggests a reason for apparently conflicting experimental results concerning tip clearance effects which may be found in the literature.

In moderate-speed turbine rotors, with typically less blade stagger at the tip than with the high-speed rotors, it may not be possible to reduce the scraping effects sufficiently. For such turbines where the centrifugal stress problems are not too acute, shrouding of the rotors may be a more likely method of blade-tip loading control.

CONCLUDING REMARKS

A clear picture of some of the secondary-flow patterns in rectangular bends was readily obtained using the smoke flow-visualization method. Passage vortex formation at the suction surface with subsequent shifting of the secondary-flow material out toward the main stream was presented pictorially. Comparisons of the boundary-layer flows in cascades and in bends disclosed that direct application of the results of study of secondary flows in bends to secondary flows in blade rows may not be valid.

The tandem cascade investigation demonstrates the peculiar, although not completely unexpected, resistance to turning of the secondary-flow vortices as they extend downstream. This behavior may explain in part the appreciable size of the losses sometimes attributed to secondary flows in turbomachines, despite the fact that the energy involvement in vortex formation is slight.

In a very preliminary sort of investigation, it was found that a balance between the passage vortex forces, the tip clearance forces, and the scraping effects of the blades on the moving wall could be established, which resulted in improved flow conditions throughout the passage and its boundary-layer regions.

Two lines of investigation that might well be undertaken profitably are suggested by these smoke studies: (1) The behavior of vortex tubes and vortices in streams of moving gases in general, and in turbomachines in particular, should be studied in order to understand how some turbomachine losses arise and perhaps how to avoid them. (2) As indicated in this report, the likelihood that the flow conditions at the blade ends of turbine rotors can be controlled in such a way as to yield improved blade-tip loading characteristics indicates the importance of initiating such an investigation. Future investigations might evaluate carefully the pertinent flow phenomena at the blade ends and seek to regulate them by varying the appropriate turbine parameters according to the considerations introduced in this report. A program of this sort might well lead directly to improved turbine design techniques.

2797

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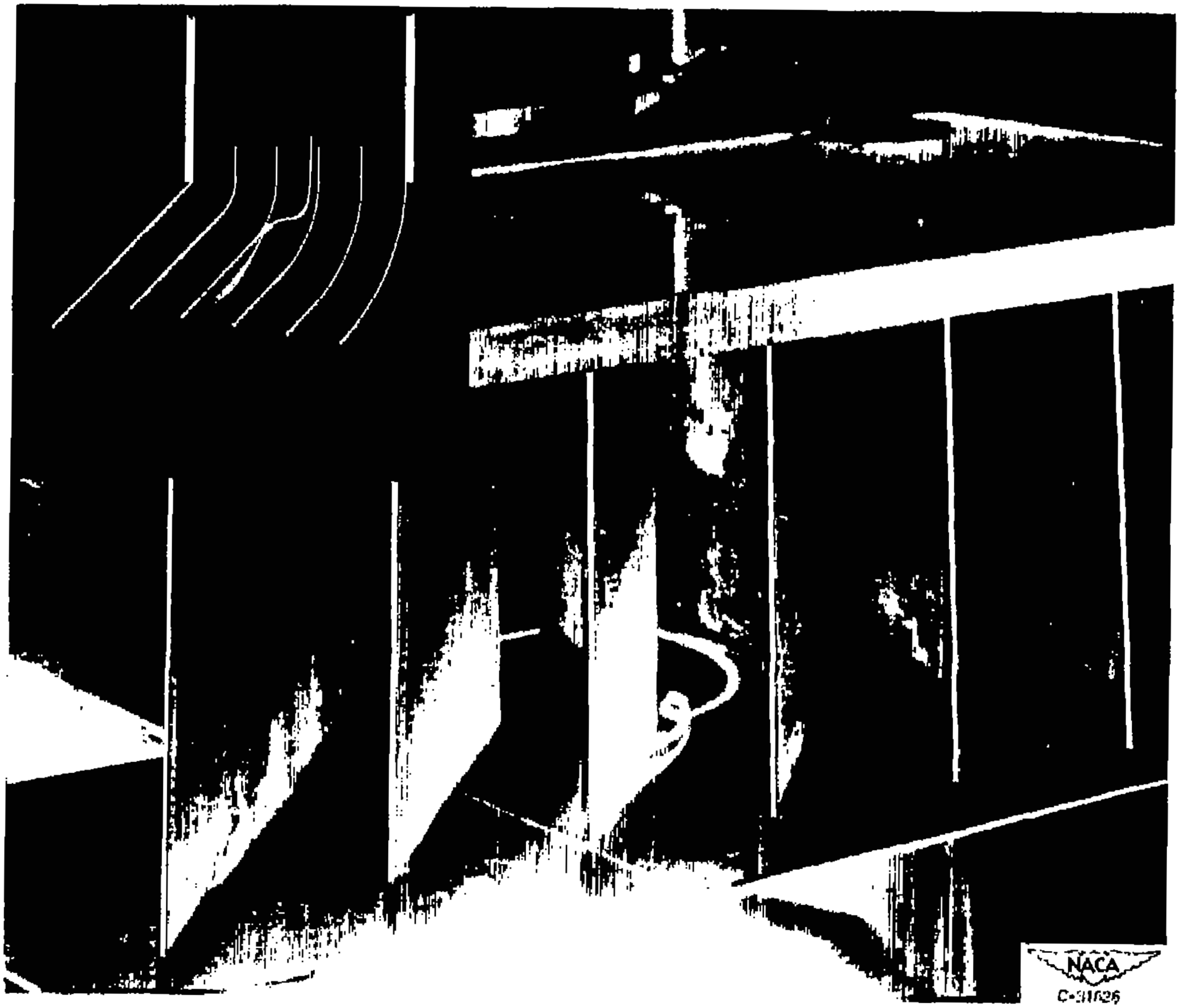


Figure 1. - Roll-up of wall inlet boundary layer to form passage vortex in 45° rectangular bend. Smoke introduced on wall near blade pressure surface.

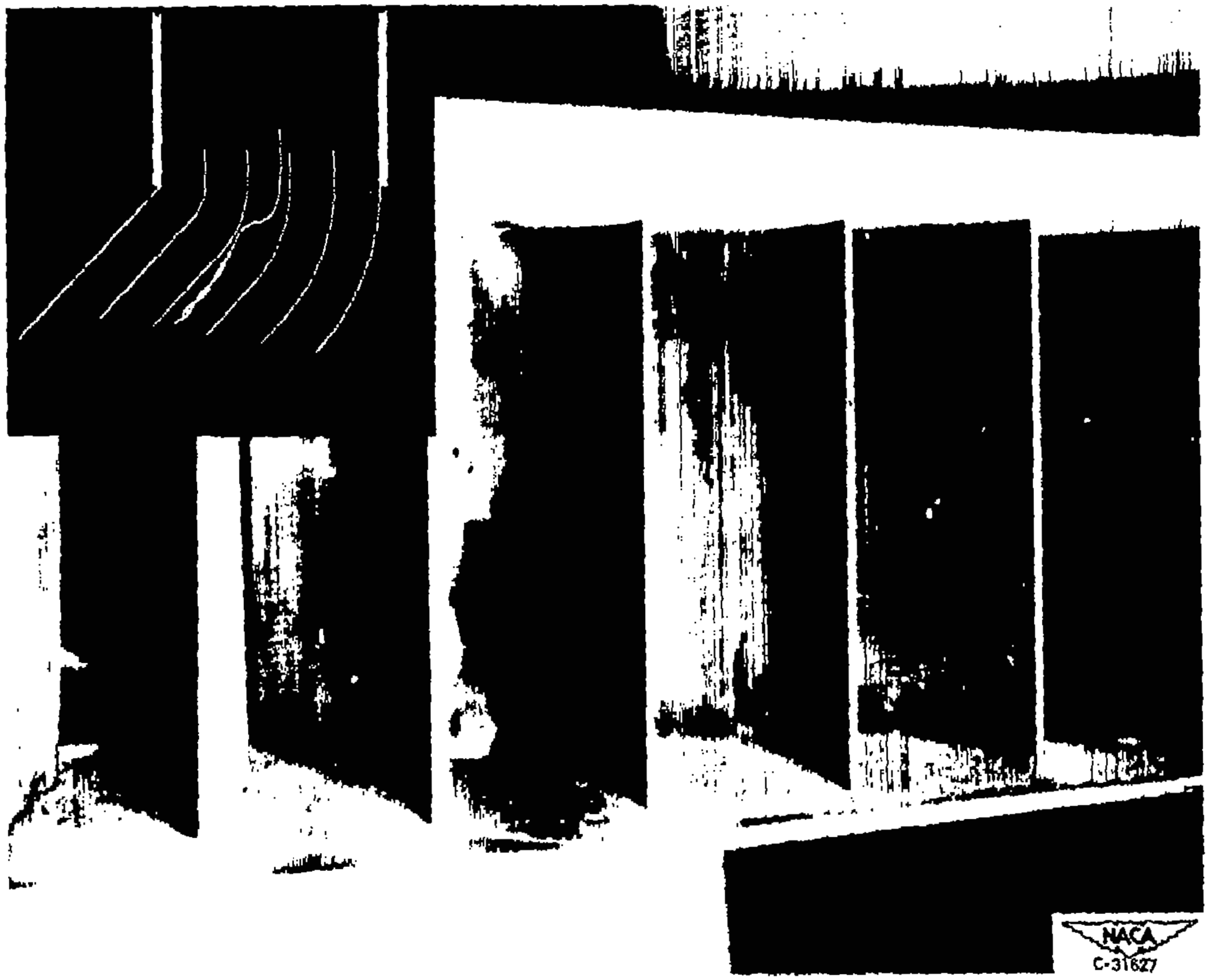


Figure 2. - Passage vortex in 45° rectangular bend. Smoke introduced on wall near blade pressure surface.

Figure 3. - Shift of secondary-flow passage vortex into main stream of 45° rectangular bend. Smoke introduced on wall near midchannel position.

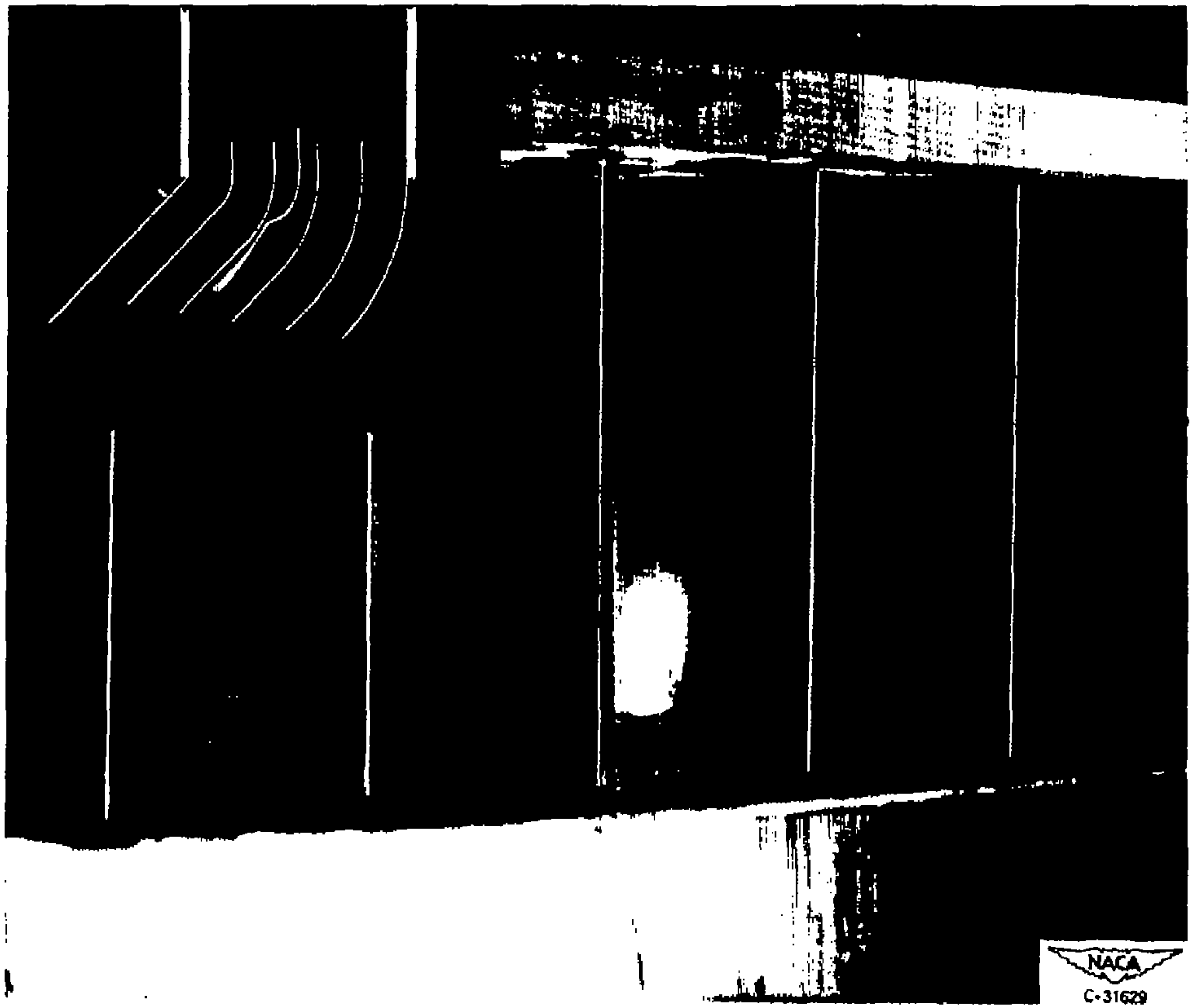


Figure 4. - Accumulation of secondary-flow passage vortex material near suction surface of 45° rectangular bend. Smoke introduced on wall near midchannel position.

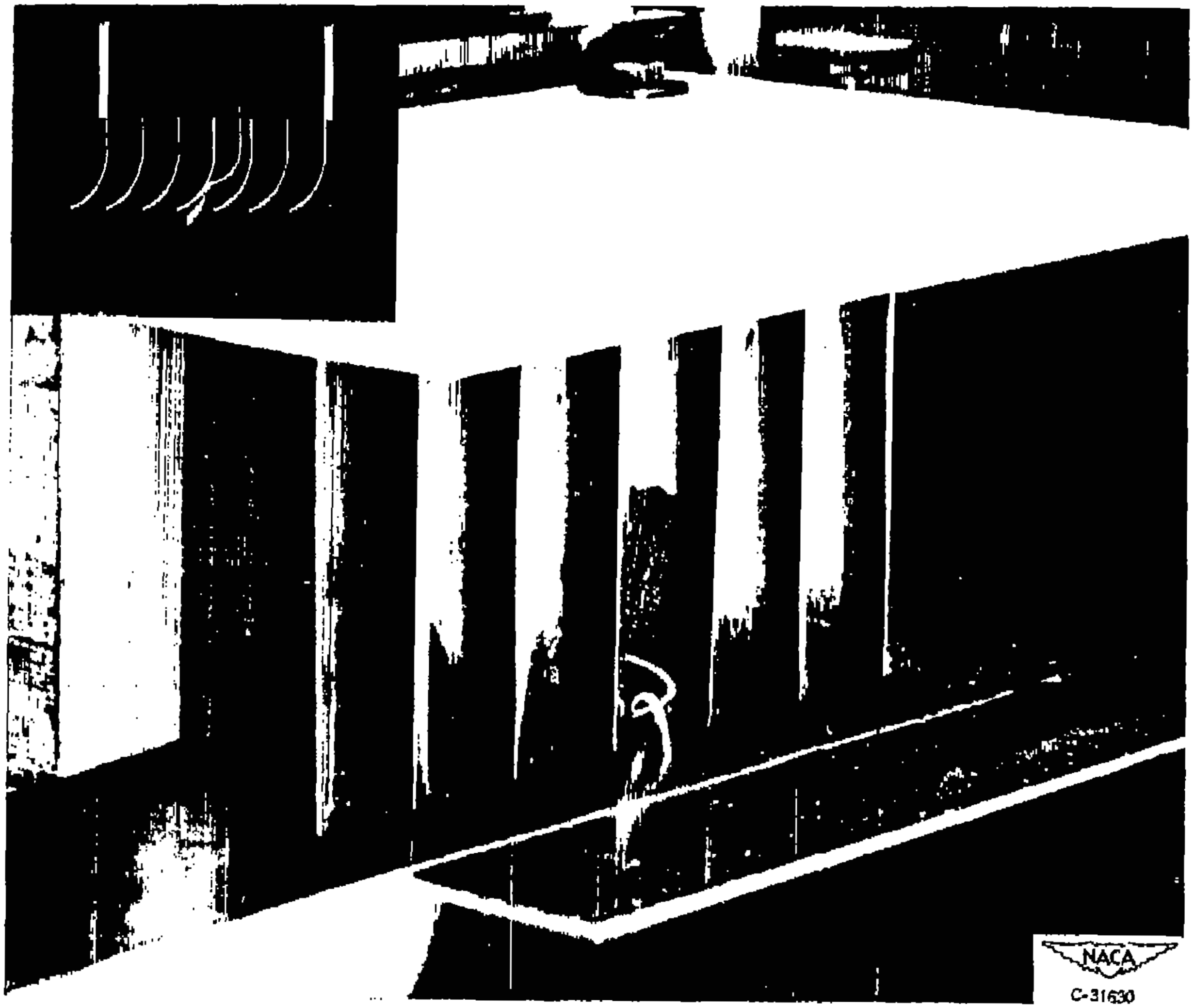
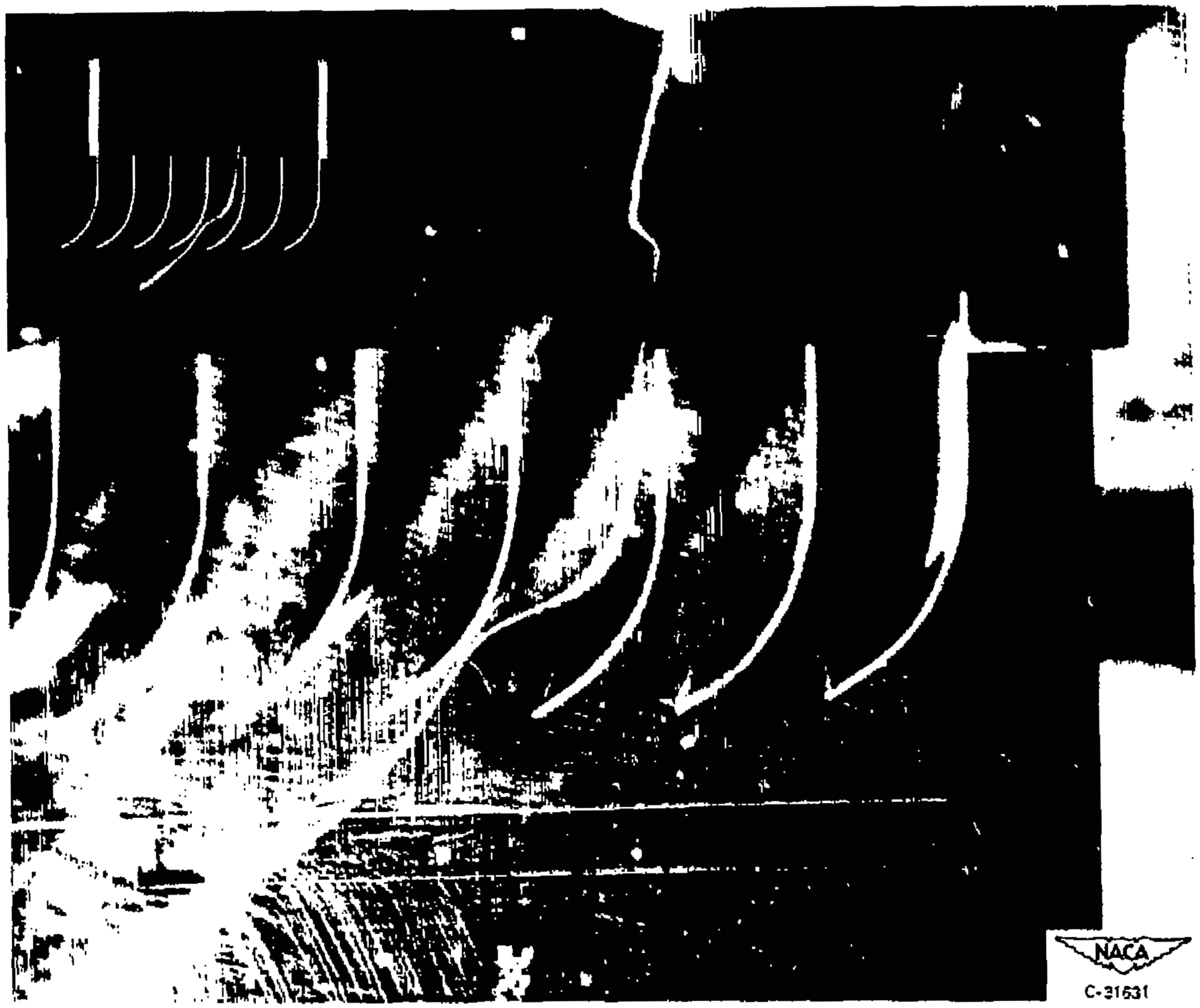
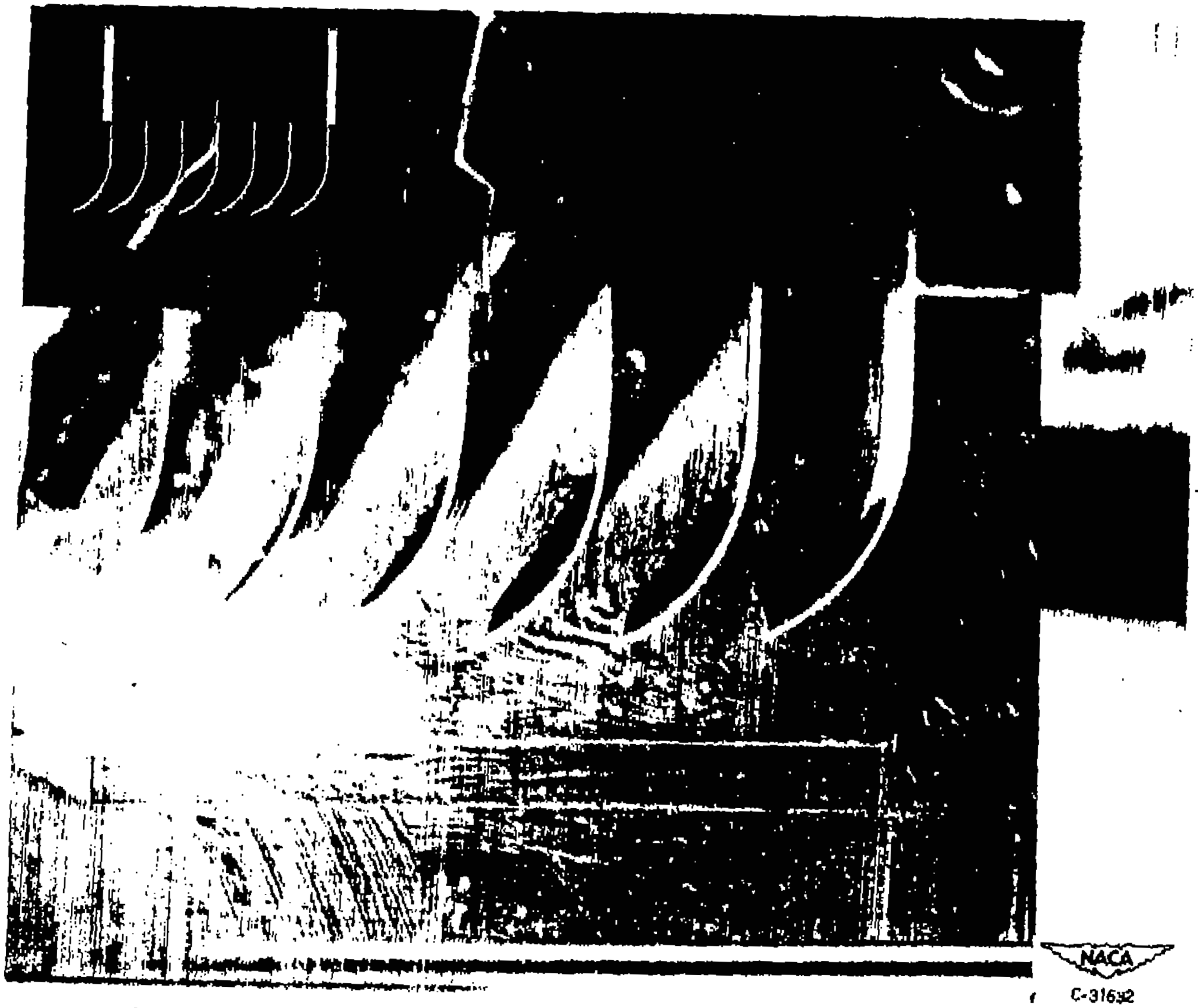


Figure 5. - Roll-up of wall inlet boundary layer to form passage vortex in 60° rectangular bend. Smoke introduced on wall near blade pressure surface.

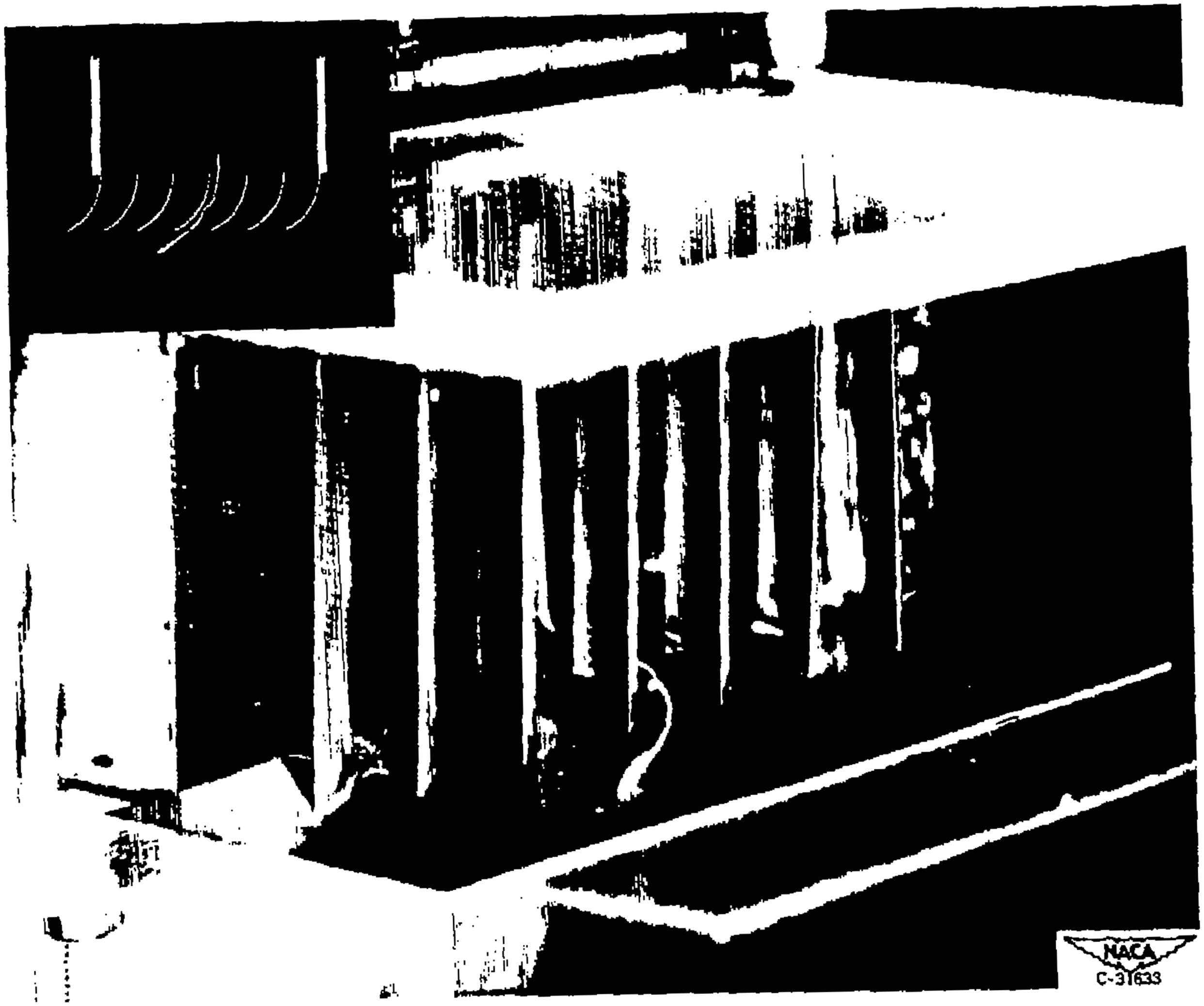


(a) Probe on wall in passage at inlet to 60° rectangular bend.



(b) Probe on pressure surface one-fourth inch from wall in 60° rectangular bend.

Figure 8. - Secondary-flow deflection across channel in 60° rectangular bend.



(a) Roll-up of wall boundary layer to form passage vortex. Smoke introduced on wall near suction surface.

(b) Roll-up of wall boundary layer to form passage vortex. Smoke introduced at wall near midchannel position.

Figure 7. - Formation of secondary-flow passage vortex in 60° cascade of blades.

(c) Deflection of flow off blade pressure surface across passage into passage vortex.

Figure 7. - Concluded. Formation of secondary-flow passage vortex in 60° cascade of blades.

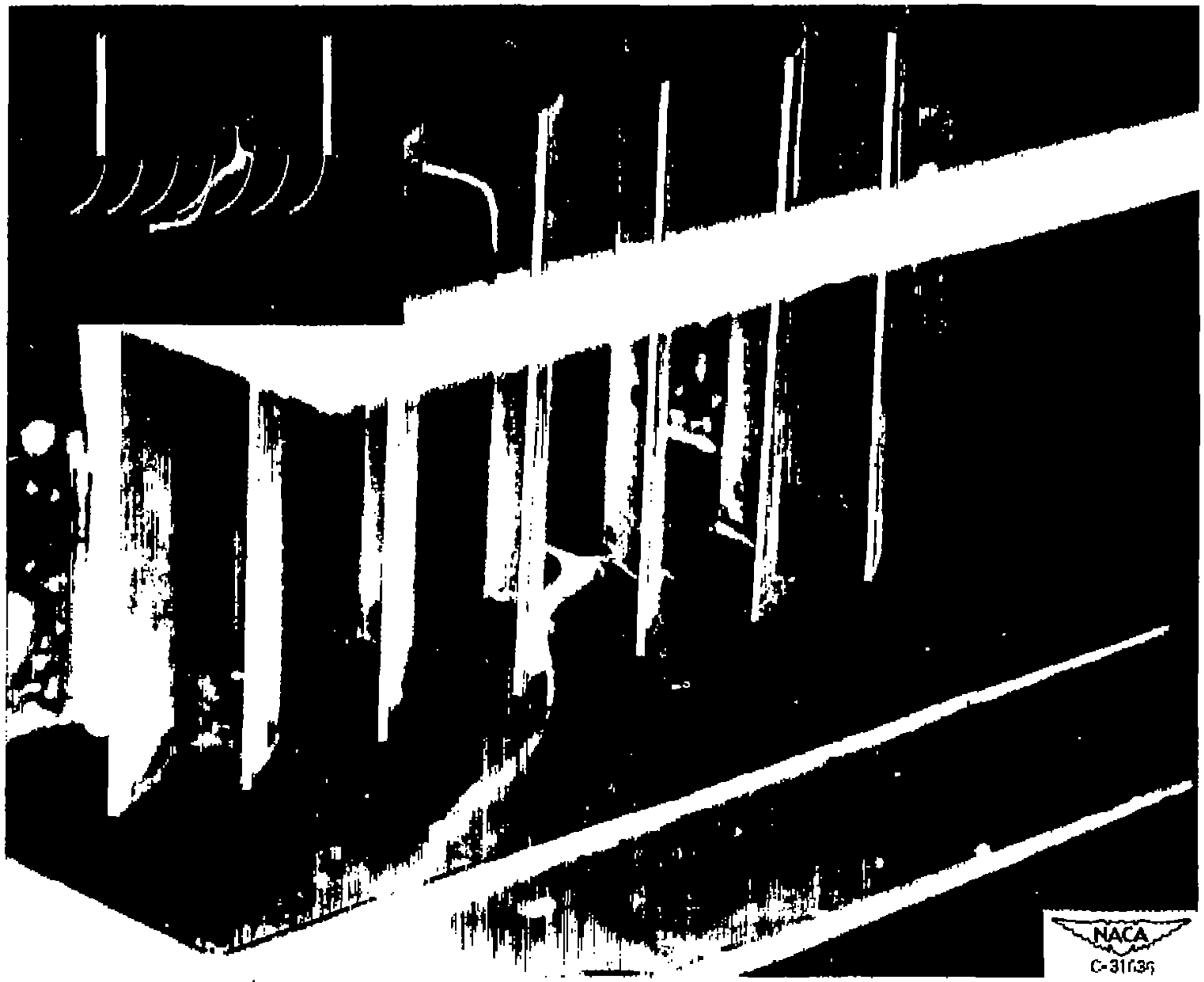
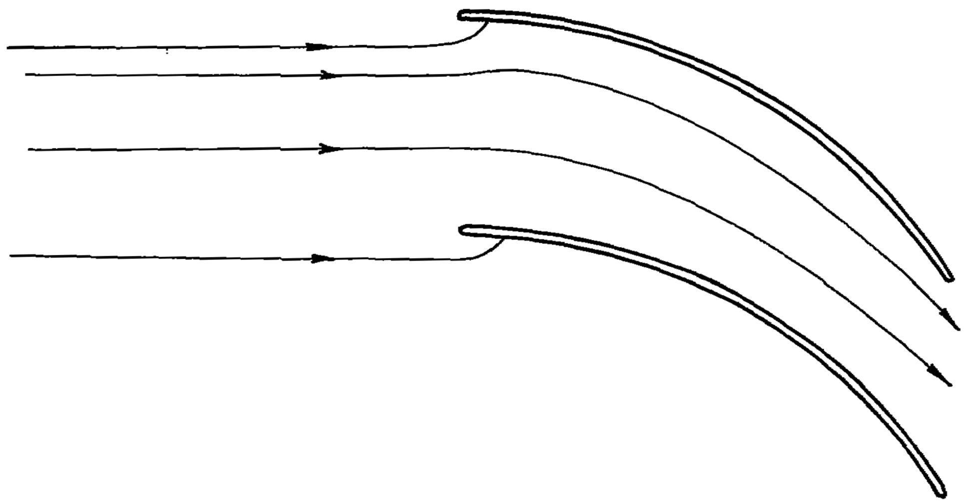
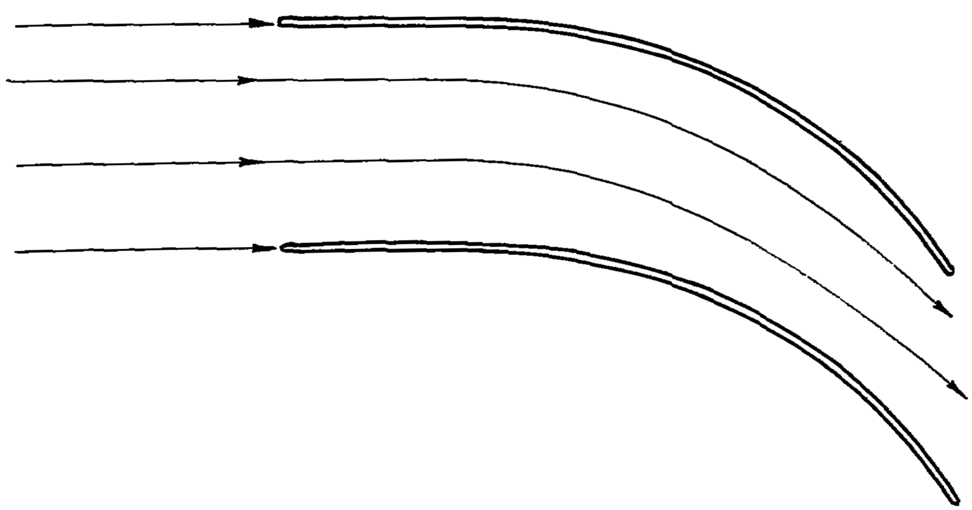


Figure 8. - Nose effects in boundary layer of 60° cascade of blades. Smoke introduced on wall near midchannel position.

Figure 9. - Overhead view of nose effect in 60° cascade of blades. Smoke introduced on wall.

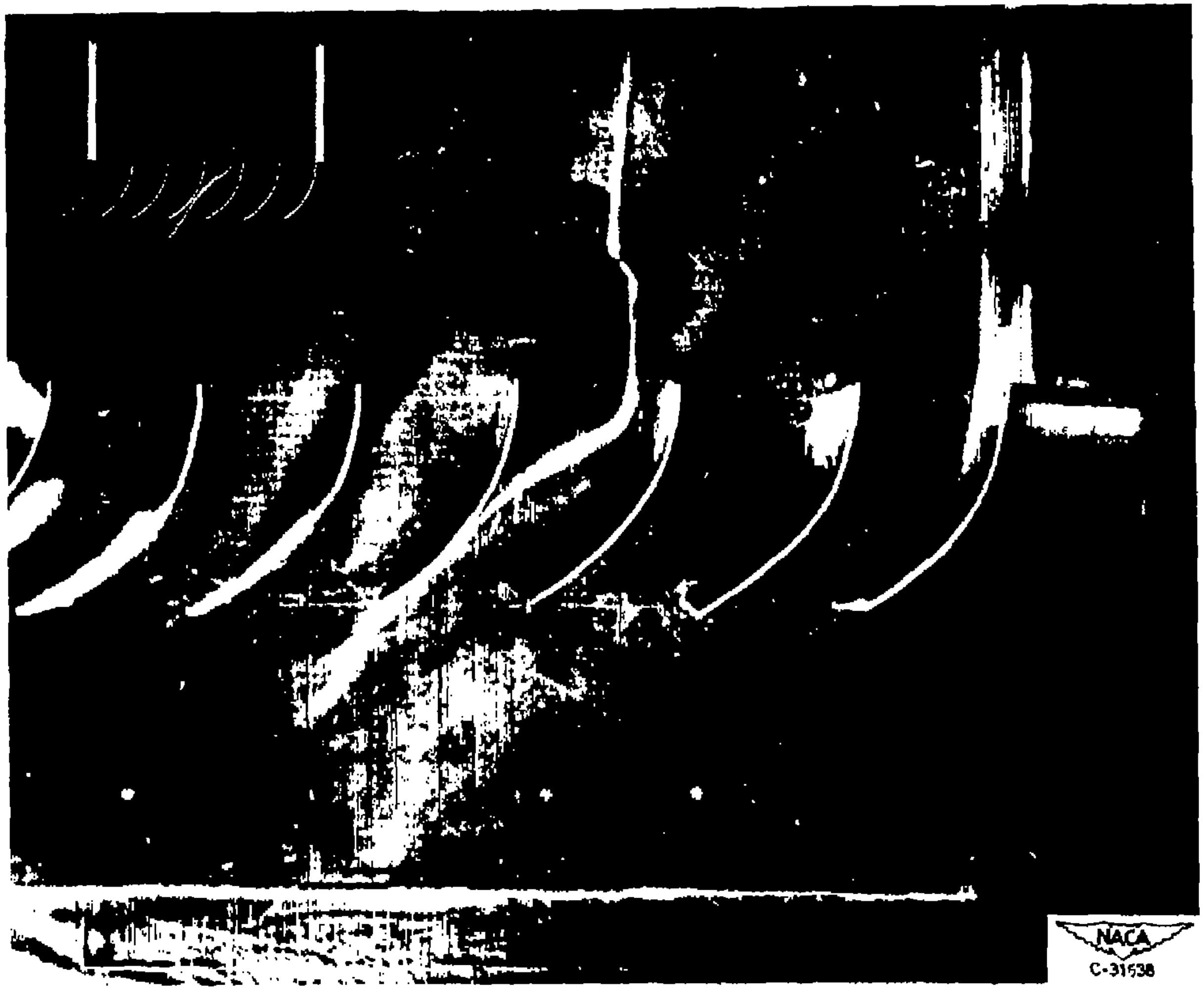


(a) Streamline pattern in 60° cascade.

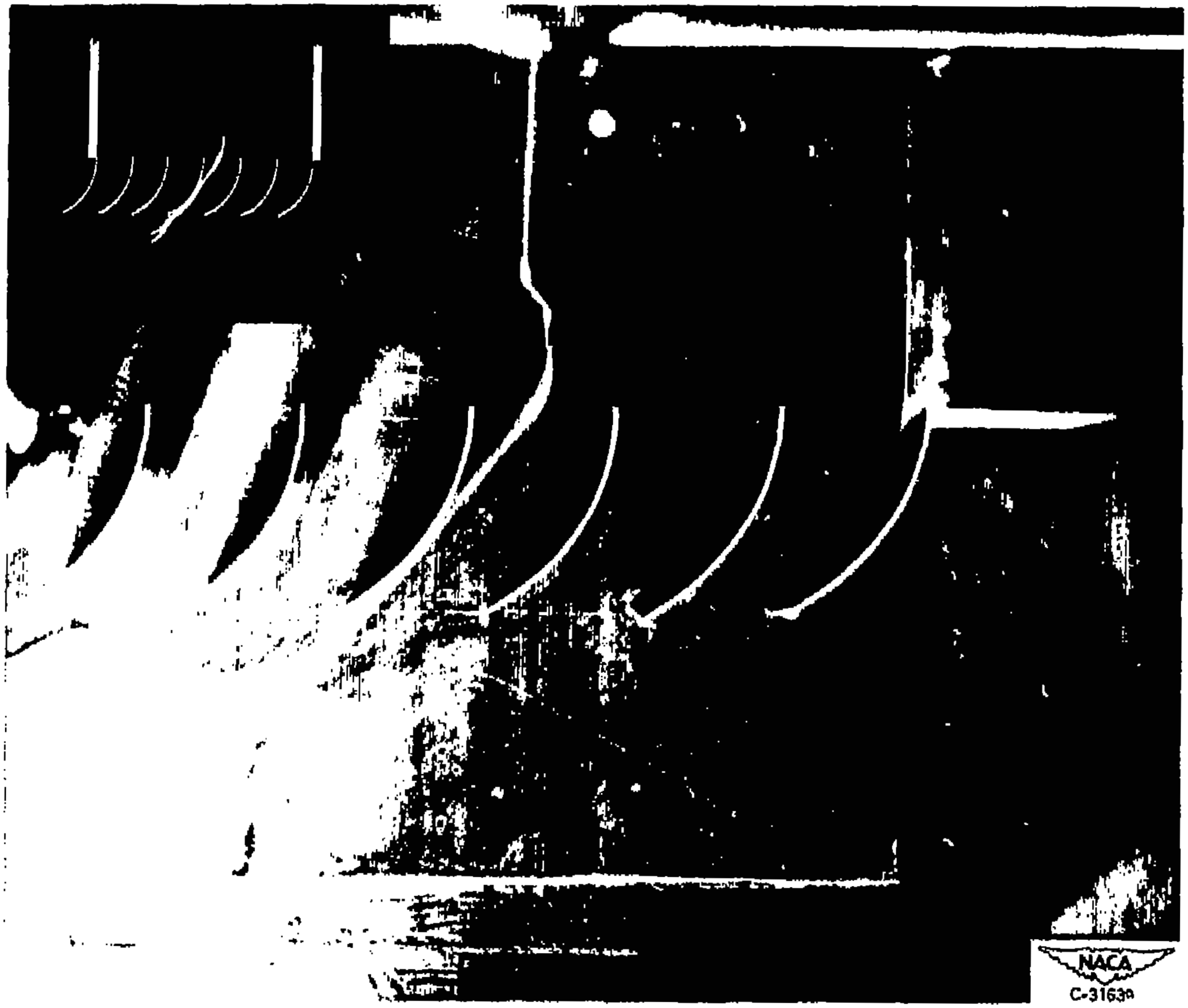


(b) Streamline pattern in 60° bend.

Figure 10. - Comparison of streamline patterns in 60° cascade and 60° bend.

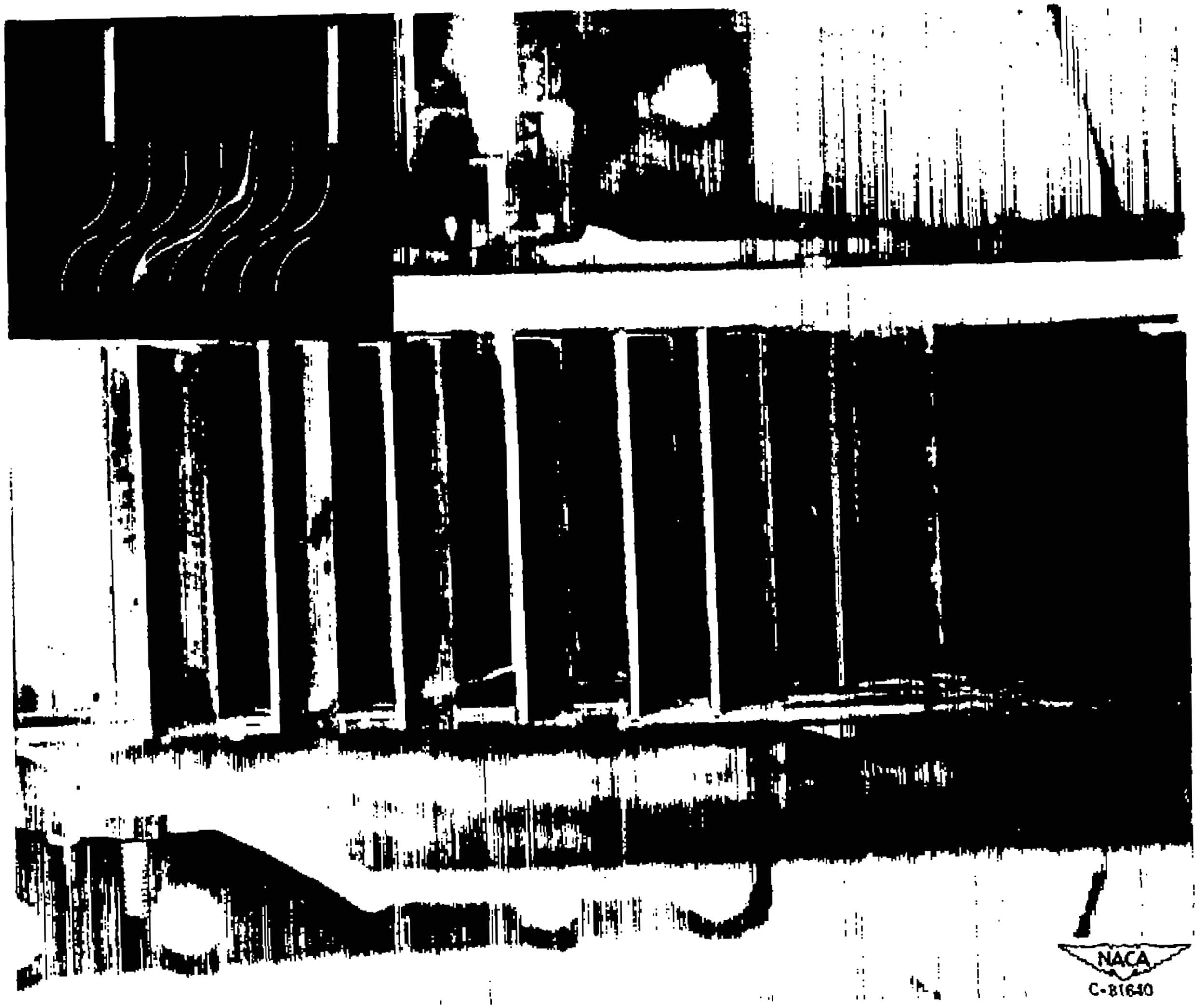


(a) Smoke trace just outside nose stagnation region.

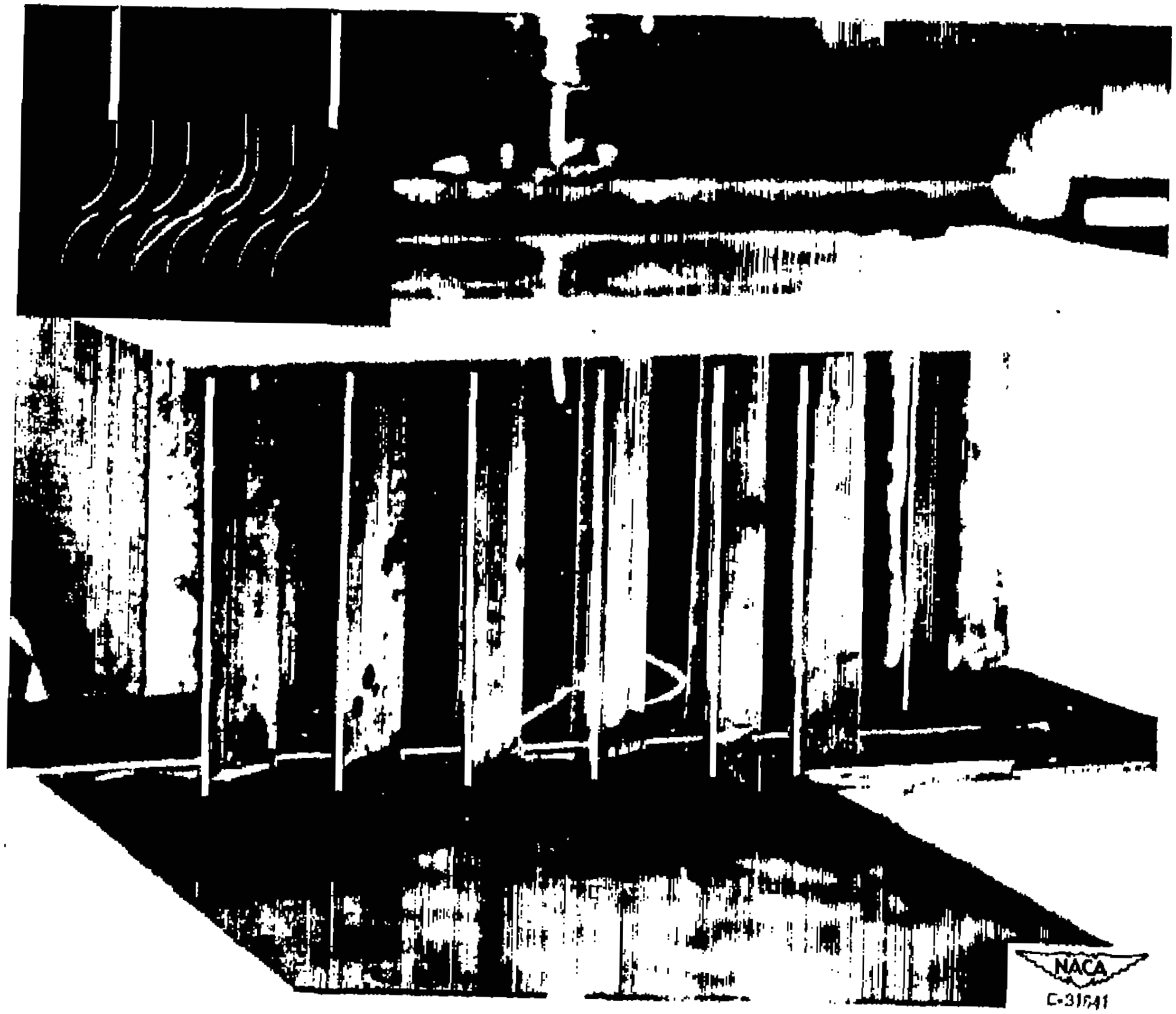


(b) Smoke trace near suction surface at inlet.

Figure 11. - Secondary-flow streamlines in boundary layer of 60° cascade showing effects of stagnation region near nose.

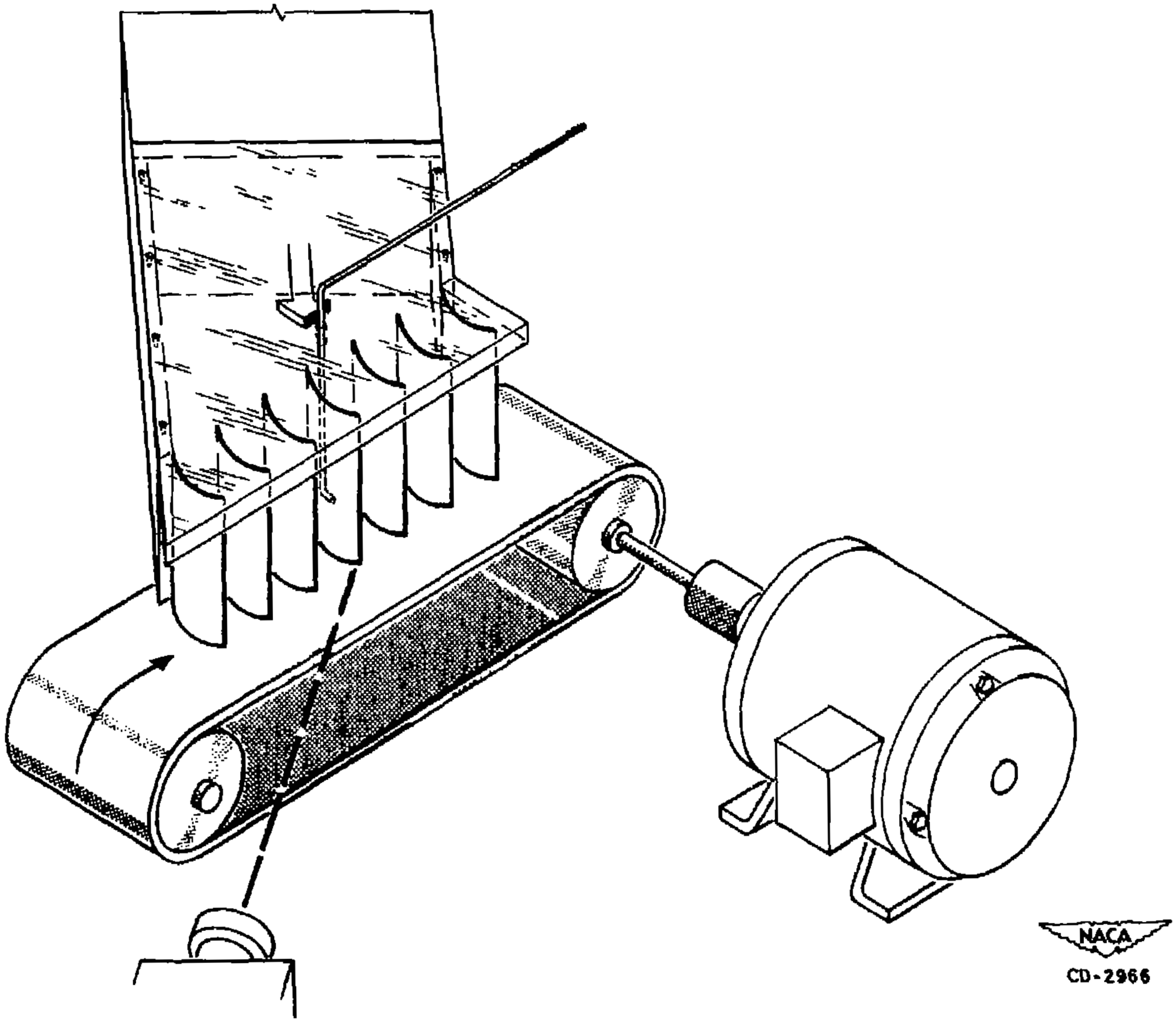


(a) Probe on wall at inlet to upstream cascade near pressure surface.

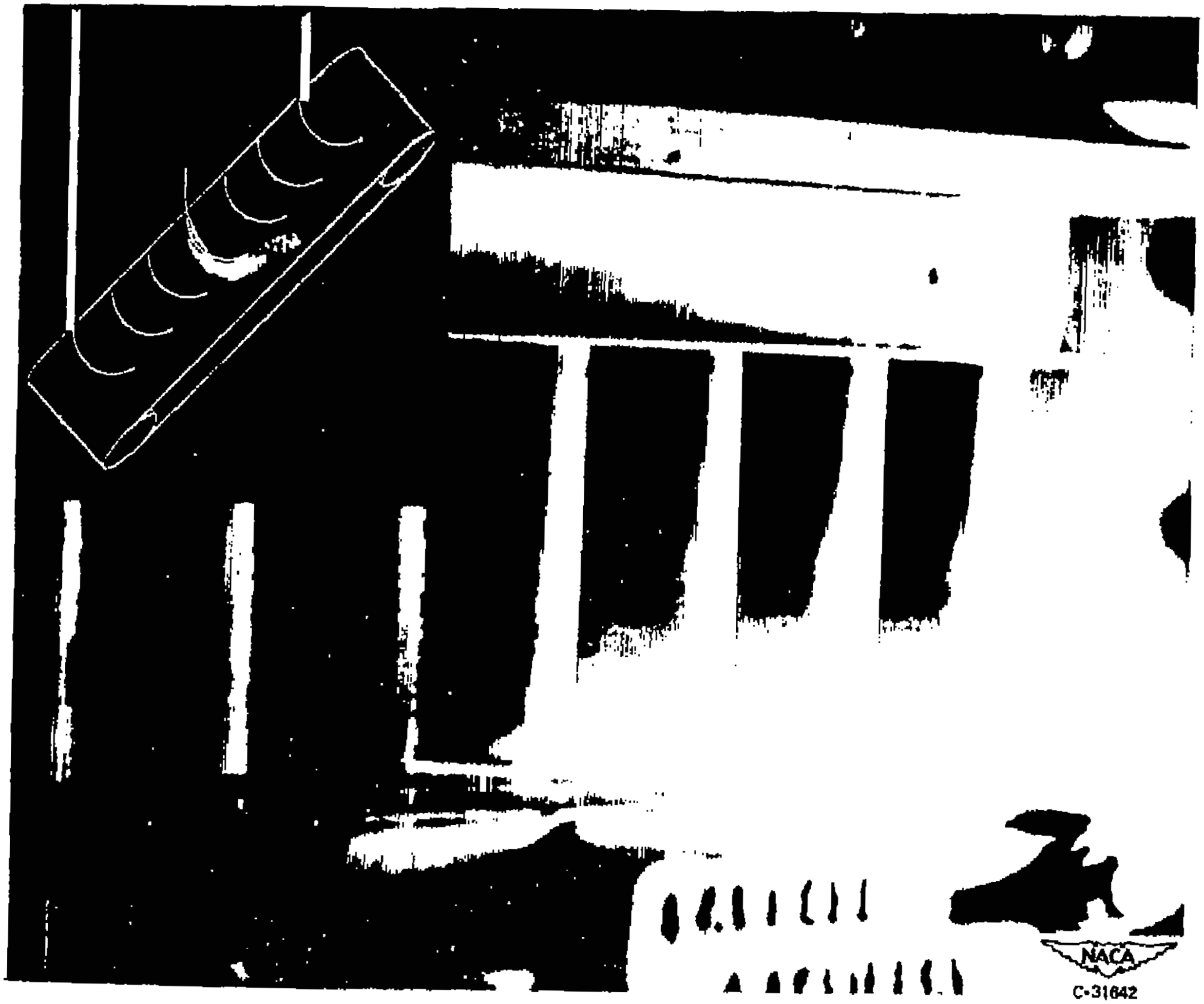


(b) Probe on wall at inlet to upstream cascade near suction surface.

Figure 12. - Passage vortex generated by upstream cascade striking pressure surface of blade in downstream cascade.

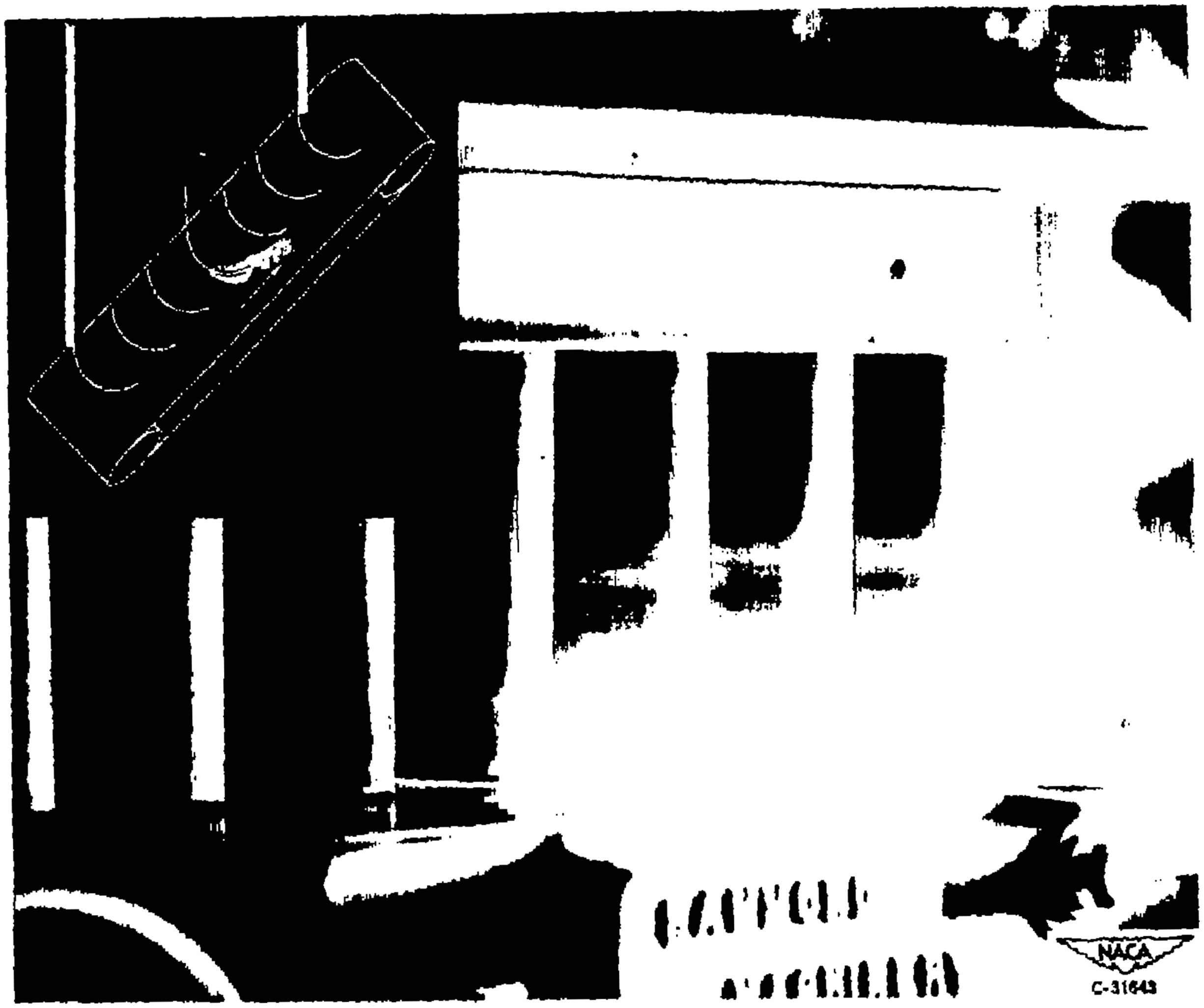


(a) Schematic diagram of apparatus.



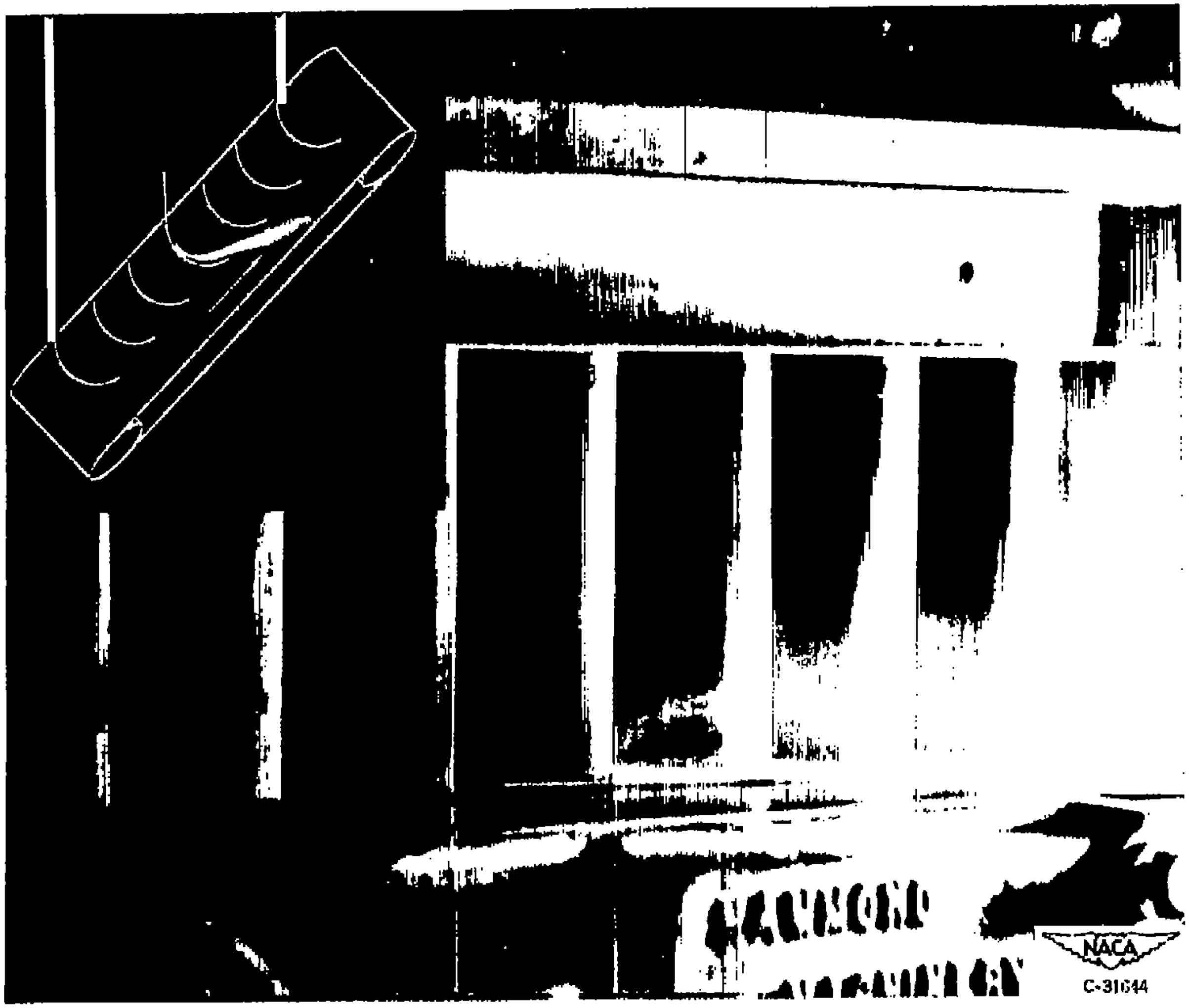
(b) Stationary wall.

Figure 13. - Tip clearance effects with relative motion between wall and high-turning blades. Smoke introduced on pressure surface of middle blade.



(c) Moderate-speed wall

NACA-Langley - 3-11-53 - 450



(d) High-speed wall.

Figure 13. - Concluded. Tip clearance effects with relative motion between wall and high-turning blades. Smoke introduced on pressure surface of middle blade.